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Semi-analytical Framework for Precise Relative Motion in Low Earth Orbits

Several multi-satellite mission architectures in Low Earth Orbits (LEO) as formation-flying, spacecraft clusters and active debris removal ask for accurate modeling of the relative motion between objects in neighboring orbits. The closer the region of interaction, the higher the level of autonomy the Guidance Navigation and Control (GNC) system may require to accomplish the mission's tasks. Hence, a precise semi-analytical framework reveals a convenient tool to support the development of efficient relative GNC algorithms.

In this context, Orbital Elements (OEs) based parameterizations are often exploited since, from the one hand, the linearization with respect to the orbit of the chief satellite remains accurate enough for quite large relative distances. From the other hand, the development of guidance algorithms can exploit the planetary variational equations to find the most efficient locations of the orbit correction maneuvers. Among the various parametrizations proposed in the literature, here the Relative Orbit Elements (ROEs) inherited from the colocation of geostationary satellites and afterwards adapted to the formation-flying field are employed. These are non-singular for small eccentricities, allow easy inclusion of the concept of passive safety of the formation through a certain relative eccentricity/inclination vector separation, and support a straightforward geometrical interpretation of how the geometry of the relative orbits changes under the effect of impulsive maneuvers.

The inclusion of the effects of the first terms of the geopotential (e.g., till 6th order and degree) modeling the non-homogenous Earth mass distribution can be conveniently accommodated in the ROEs framework. First, short- and long-periodic terms are removed through an analytical transformation combining a Lie-series based approach, closed form in eccentricity, and the Kaula method. Afterwards, the ROEs secular variations, due to J_2, J_2^2, J_4 and J_6 terms, are recovered through the first order expansion of the time derivatives of such mean set with respect to the chief's orbit.

Differential aerodynamic drag is the second dominant perturbation in the LEO region, with an effect proportional to the differential ballistic coefficient between the considered spacecraft. As for OE-based formulations, the proposed techniques so far either exploit an engineer approach or a physical one. The first method relies on a general empirical formulation of the differential drag acceleration to include the mean effects produced on the ROEs. Whereas the latter methodology directly expands the time derivatives of the averaged OEs subject to a drag acceleration with an exponential density model. Both approaches require the inclusion of additional parameters to the ROE state variables and the investigation of their physical meaning, as well as their relationship, is beneficial to understand their effect on the ROEs' evolution.

In addition to the description of the aforementioned building blocks, the paper focuses on their interfacing, to set-up a fully consistent framework. The resulting performances in terms of achievable propagation accuracy are critically presented together with the framework's validity ranges.

Summary

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